A Systems Engineering Approach to Quality Assurance for Aerospace Testing

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On the surface, it appears that AS9100[1] has little to say about how to apply a Quality Management System (QMS) to major aerospace test programs (or even smaller ones). It also appears that there is little in the quality engineering Body of Knowledge (BOK)[2] that applies to testing, unless it is nondestructive examination (NDE), or some type of lab or bench testing associated with the manufacturing process. However, if one examines: a) how the systems engineering (SE) processes are implemented throughout a test program; and b) how these SE processes can be mapped to the requirements of AS9100, a number of areas for involvement of the quality professional are revealed. What often happens is that quality assurance during a test program is limited to inspections of the test article; what could be considered a manufacturing *al fresco* approach. This limits the quality professional and is a disservice to the programs and projects, since there are a number of ways that quality can enhance critical processes, and support efforts to improve risk reduction, efficiency and effectiveness.

The Systems Engineering (SE) discipline is widely used in aerospace to ensure the Quality Assurance for Aerospace Testing progress from Stakeholder Expectations (the President, Congress, the taxpayers) to a successful, delivered product or service. Although this is well known, what is not well known is that these same SE processes are implemented in varying complexity, to prepare for and implement test projects that support research, development, verification & validation, qualification, and acceptance test projects. Although the test organization's terminology may vary from the SE terminology, and from one test service provider to another, the basic process is followed by successful, reliable testing organizations.

For this analysis, NASA Procedural Requirements (NPR) 7123.1, *NASA Systems Engineering Processes and Requirements[3]* is used to illustrate the SE processes that are used for major aerospace testing. Many of these processes are also implemented for smaller test projects, and this set of processes will also look familiar to those who have participated in launch site activation and flight demonstrations.
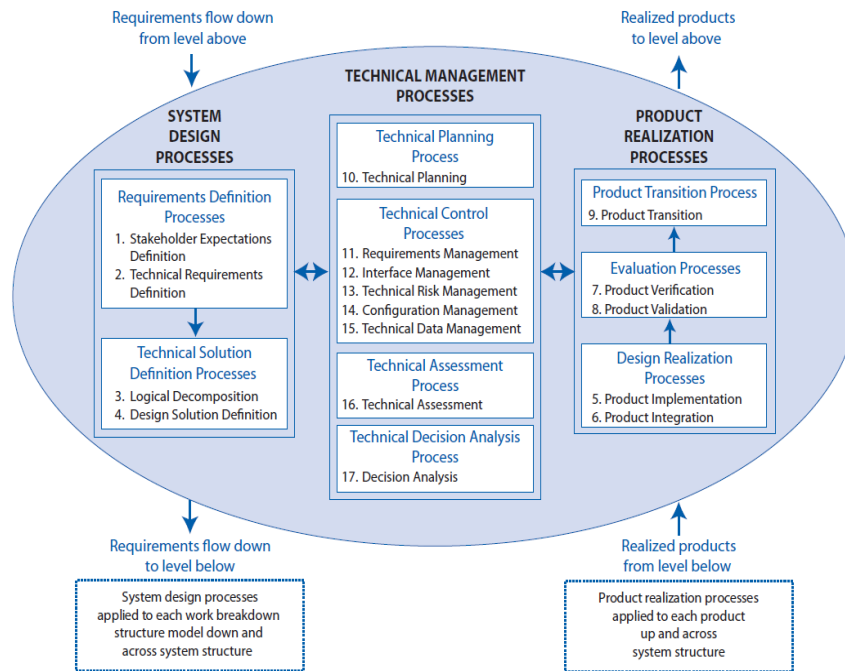
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[1] SAE AS9100 *Quality Management Systems - Requirements for Aviation, Space and Defense Organizations*

[2] http://cert.asq.org/certification/control/quality-engineer/bok

[3] http://nodis3.gsfc.nasa.gov/displayDir.cfm?t=NPR&c=7123&s=1B

Figure 1   NPR 7123.1 Systems Engineering "Engine"

Requirements flow down from level above

Realized products to level above

TECHNICAL MANAGEMENT PROCESSES

SYSTEM DESIGN PROCESSES

PRODUCT REALIZATION PROCESSES

Technical Planning Process
10. Technical Planning

Product Transition Process
9. Product Transition

Requirements Definition Processes
1. Stakeholder Expectations Definition
2. Technical Requirements Definition

Technical Control Processes
11. Requirements Management
12. Interface Management
13. Technical Risk Management
14. Configuration Management
15. Technical Data Management

Evaluation Processes
7. Product Verification
8. Product Validation

Technical Solution Definition Processes
3. Logical Decomposition
4. Design Solution Definition

Technical Assessment Process
16. Technical Assessment

Design Realization Processes
5. Product Implementation
6. Product Integration

Technical Decision Analysis Process
17. Decision Analysis

Requirements flow down to level below

Realized products from level below

System design processes applied to each work breakdown structure model down and across system structure

Product realization processes applied to each product up and across system structure

In studying the Seventeen Processes of the SE "Engine", quality assurance professionals will find many opportunities to apply the lessons from Deming[4] and Crosby[5] for process improvement and defect prevention (e.g. planning, design, continual improvement, supplier and process capability assessments, process control, education and training), and will learn that quality assurance as related to testing is not limited to quality control inspections after the test article is delivered to the test site.   It is important to note also that many project managers and systems engineers, acting as test customers, are not fully aware of the complex systems engineering processes required to fulfill their agreements with testing organizations. This can result in increased technical and project risk.

The complexity of the processes will depend upon the life cycle phase (e.g., research vs. qualification), the level of the test article and/or software (e.g., component vs. system), the type of test (e.g., subscale wind tunnel test vs. integrated stage hot fire), and other factors such as the use of heritage hardware, or repeated testing at the same test location. It is important to note that

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[4] http://asq.org/learn-about-quality/total-quality-management/overview/deming-points.html
[5] http://asq.org/learn-about-quality/cost-of-quality/overview/overview.html

these processes also take place at launch sites, but for simplicity, this analysis will use the word "test".

The graphic shown above from NASA's NPR7123.1, is used for the following discussion. Processes 1 and 2, Stakeholder Expectation Definition and Technical Requirements Definition, respectively, are mainly performed at the project level (i.e., identification of mission, integrated systems, systems, subsystems, components) before the testing organization is contacted. However, information at this point is often preliminary, and the testing organization may participate in this process in parallel with Technical Planning (Process 10) very early in the life-cycle, especially if new facilities and/or hardware are needed. In the interest of maintaining a schedule, this entire process can be iterative, often with final requirements and as-built drawings being completed in time for the Test Readiness Review, which is a type of Technical Assessment (Process 16). Therefore, each organization needs some level of work tracking and constraint checks to confirm readiness (i.e. Configuration and Data Management (Processes 14 and 15).

The Test Team must go through the logical decomposition process (Process 3) with the customer's Test Requirements Document in order to thoroughly understand the required parameters and derived requirements. They must begin the process of identifying test equipment, test facilities, support equipment, fixtures, software needs, and instrumentation. This is closely followed by design of equipment, fixtures, new facilities or modifications, data channels, and coding of software (Process 4).

The Test Team and the customer must engage in Technical Planning (10) and other Technical Control Processes (11-15) throughout this activity. Depending on the magnitude of the effort, this could be an iterative process that could take many months. Technical requirements, trade studies, cost, schedule, safety, quality assurance, environmental regulations, logistics, calibration, procurements, workforce staffing and training, permits and certifications, codes and standards must be identified, managed (Process 11), implemented and tracked. Requirements changes from the customer must be factored in and schedule adjustment may be necessary, depending upon the timing and magnitude. Interface Management (12) is part of this overall planning and control process, since test article-to-equipment interfaces must be identified and tracked, as well as each interface at the facility, equipment, and fixture level. For purposes of mapping to AS9100, this relates to Configuration Management. Depending on the complexity of the test and test article, some type of Interface Control Document may be required.

Technical Risk Management (Process 13) can also be a significant aspect of preparations, again, depending upon the magnitude of the effort. Much of this activity proceeds at some level of risk, due to the fact that many customer requirements are still preliminary. Consequently, facility and equipment fabrication may have to proceed with preliminary drawings, in some cases. It is often accepted that the schedule risk of changes to test article and/or test requirements, resulting in redesign of the facility or equipment, has a high probability, but lower

consequences, than the cost and schedule risk of waiting until later in the life cycle to begin the process.

Configuration of facilities, fixtures, software, and equipment and of the work authorizing documentation must be carefully managed (Process14) and all associated documents, drawings, reports, calculations, analyses, and test data must be managed and maintained in an accessible records system (Process 15). This is vital to the Technical Assessment (i.e. test readiness review, hazard analysis) Process (16), and for use of the data by the customer.

At some point during the early and later planning stages, purchases are made and products delivered, such as off-the-shelf valves, tubing, equipment, instrumentation, computers, and possibly liquid propellants or pressurizing gases. Test organizations often have the ability to fabricate facility modifications, support equipment, and test equipment. This is Product Implementation for the test organization, in order to be configured for a specific test article (Process 5). It should be noted that the industry codes and standards, which provide the safety and reliability of the test facilities and equipment, are based on very exacting industry quality assurance methods and controls. There may also be support operations such as precision cleaning and calibration laboratories, which must meet exacting standards. Test software must be coded and configuration controlled. Test facility hardware and software must be installed and integrated (Process 6). This process will eventually include integration of the test article with the test facility or equipment. This includes hardware, control software, and instrumentation.

Verification (Process 7) and Validation (Process 8) ("V&V") are also required for the test facility, equipment and software. For safe and reliable operations, all new or modified systems, along with existing systems, must be "baselined" through some type of inspection and analysis process, and tested to determine whether the systems are performing as expected and required, including both planned commands and emergency shutdown. Additional V&V activities may be required after the test article is integrated into the facility system. This could include various types of checkouts, such as proof testing, cold flows, ignition testing, pathfinders, engineering units and calibration samples and sequence runs. There may be some type of Operational Readiness Review (Process 16) in parallel with this design, integration and V&V process that is required by the test organization separately from the customer's processes (although a project review can be done in conjunction with a facility review).

All of this leads up to the Test Readiness Review (Process 16), at which time a board is convened to assess readiness of facility, test article, and crew; safety plans for personnel, facilities, and operations; risk, adequate level of quality assurance, environmental compliance, emergency shutdown capabilities, and other pertinent topics. Once permission to proceed with testing is granted, the V&V *of the test article* can begin, based on the customer's requirements. Depending on the test, many months of planning, fabricating, purchasing, integrating and facility V&V must take place before this point.

The test article is transitioned back to the test customer once the test or test series is complete (Process 9). The Test Team may participate in data reviews to support the Decision Analysis (Process 17) that the customer must perform. Product Transition, in reality, is the delivery of the *test data*, which is provided in some pre-determined electronic or hard copy format, along with any required documentation. The testing organization is responsible for the integrity of the test data, while validation of the test article's performance is the responsibility of the customer.

Some extrapolation is required to apply AS9100 to a testing lab, since testing is a unique combination of building and maintaining infrastructure, and providing a service that requires this infrastructure. However, once the foundation is laid for understanding the implementation of SE processes in a testing environment, the next step is to map the SE processes to AS9100, as shown in the table below. Once the relationship between AS9100 and SE, and between SE and test organization processes becomes clearer, it can be seen how a QMS can be developed and implemented that serves the testing organization, rather than forcing a product manufacturing paradigm onto a testing service. This understanding is vital, since shortcuts in quality assurance may actually be shortcuts in the SE processes.

One final caveat for the auditors: The measure of the effectiveness of a testing organization is found in the test data. It is the data that reveals whether the customer's requirements have been met, for example, by the test sequence, in recorded temperatures, pressures, flow rates, durations, loads, acoustics, and many other types of inputs. Test procedures are often the necessary steps to prepare for the test and to condition the test article. The test itself may in fact be run by the test control computer and recorded by instrumentation, often on several hundred data channels at several hundred samples per second. The test procedure may not be the build-paper equivalent that the auditors are looking for, since much of it is often facility related.

Table 1 Systems Engineering Processes Mapped to AS9100

SE PROCESS	AS9100 REQUIREMENT
Stakeholder Expectations	Customer Requirements
Technical Requirements Definition	Planning of Product Realization
Logical Decomposition	Design and Development Input
Design Solution Definition	Design and Development Output
Product Implementation	Control of Production
Product Integration	Control of Production
Product Verification	Verification
Product Validation	Validation
Product Transition	Control of Work Transfers; Post Delivery Support, Preservation of Product
Technical Planning	Planning of Product Realization; Review of Requirements; Measurement, Analysis and Improvement
Requirements Management	Design and Development Planning; Purchasing
Interface Management	Configuration Management
Technical Risk Management	Risk Management
Configuration Management	Configuration Management; Identification and Traceability; Control of Nonconforming Product
Technical Data Management	Control of Documents; Control of Records; Control of Design and Development Changes
Technical Assessment	Design and Development Review
Decision Analysis	Measurement, Analysis and Improvement; Analysis of Data

As can be seen, "test" can entail a significant SE effort in the life cycle of a product, which can be underestimated by project managers and overlooked by quality professionals. The application of AS9100 to test activities should not be limited to acceptance and qualification of the test article, since a QMS can be mapped to SE processes that are implemented during preparations for testing at any point in the life cycle. The aerospace quality professional needs to be able to relate AS9100 to systems engineering and to aerospace testing, so that an approach to quality assurance involvement beyond test article inspection can be formulated to achieve performance excellence.

References

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SAE AS9100 *Quality Management Systems - Requirements for Aviation, Space and Defense Organizations,* SAE International